CABLE CAPACITANCE MEASUREMENTS

CONTENTS

1. GENERAL

1.1 This section is intended to provide REA borrowers, consulting engineers, contractors, and other interested parties with technical information for use in making mutual capacitance measurements on telephone cable.

1.2 The primary purpose of this section is to describe how to make mutual capacitance measurements, how to apply the proper correction factors to these measurements, and how to analyze the measurement data. All discussion on capacitance measurements in this section refer to measurements at 1 kHz.

1.3 The measurement of cable mutual capacitance is a tool aid in determining the condition of cable. Where circumstances warrant, cables are sometimes measured on the reel before installation to determine if the cable specifications are met. Another important use for cable capacitance measurements is on installed cables. Where electronic transmission systems such as carrier are planned for use on existing cables, these cables should first be tested and determined to be suitable for their planned use. This is especially important for air core cables where the entry of moisture can affect the cable characteristics. REA TE&CM Section 921, Testing Cables for Carrier Application, indicates that mutual capacitance measurements can be used to supplement basic cable plant tests. Because capacitance measurements are most effective in short measurement lengths, they are usually made only to localize problems after other measurements raise questions about the cable condition.

1.4 The necessary information for making mutal capacitance measurements and applying correction factors to the measurement data is contained in the main body and exhibits of this section. Appendix 1 provides a simplified explanation of propagation effects on capacitance measurements.

1.5 There are several types of automatic capacitance measuring equipment available. These range from small portable instruments to large rack mounted systems. Automatic measuring instruments are sometimes used by cable manufacturers and consulting engineers for volume testing. The engineer or craftsperson is cautioned to become familiar with the measurement technique, instrument capabilities and instrument limitations when using automatic capacitance measuring instruments. Some measurement techniques (i.e., ramp wave) do not measure capacitance at 1000 hertz, and do not measure conductance or dissipation. Where new cables are suspected to be faulty, capacitance and conductance must be measured at 1000 hertz and compared to REA cable specification requirements before cables are rejected. Also, conductance is an important factor in evaluating the condition of existing cables.

2. INTRODUCTION

2.1 Before making capacitance measurements on cables, become familiar with your test equipment and the basic electrical makeup of cables. This introduction to cable measurements is intended to help the reader better understand cables, test instruments, what is being measured, and some measurement limitations.

2.11 Review the test instrument functions and limitations (such as accuracy). Apply the proper correction factors or formulas to the measurement data. Be aware of any special precautions in making measurements with your instrument such as the following:

1. What is done with all other pairs when making measurements on one pair?

2. Is the shield or other cable parts connected to ground or other special terminals?

2.12 Become familiar with the cable parameter being measured and how this measurement data is expressed. Mutual capacitance is usually measured and expressed as determined by the test instrument in one of three ways:

a. Series capacitance and dissipation (Cs & D)
b. Parallel capacitance and dissipation (Cp & D)
c. Parallel capacitance and conductance (Cp & Gp)

2.13 The capacitance bridge measures the "apparent" cable capacitance and dissipation (or conductance). True values of conductance

must always be calculated or "corrected". For longer measurement lengths, the "apparent" measurement data must be corrected to obtain true values of capacitance also.

2.14 Apply the proper correction factors. When measuring in the series mode, apply series correction factors, and when measuring in the parallel mode, apply parallel correction factors (References are listed for further study). The classic method of measuring and presenting cable capacitance data has been open circuit admittance (Yoc), or capacitance and conductance in parallel. Many of the commonly used portable capacitance bridges measure open circuit impedance (Zoc), and is expressed as capacitance and dissipation in series. Valid data can be obtained with either series or parallel bridge types if properly corrected. Examination of the correction factors show that propagation affects the series measurements less than the parallel measurements on longer measurement lengths. This can result in more accurate and less complex capacitance corrections as the cable parameters vary from nominal values. The major reason for this is that the dissipation arm of the capacitance bridge tends to balance out the cable series resistance without regard to the exact value of resistance. Refer to Appendix 1 for more discussion on this.

3. HOW TO MEASURE MUTUAL CAPACITANCE

3.1 Preliminary

3.11 Periodically use a known capacitance to check the instrument accuracy. Know your measuring instrument and its capabilities. Some capacitance and impedance bridges apparently were not originally designed to measure cable capacitance because there is not a legtimate ground terminal to make three terminal measurements. An example of this is the Electro Scientific Industries 250 DE and the General Radio 1650A which are in common use for measuring cable capacitance. These instruments must not be grounded or connected to the cable shield. Grounding shorts out a portion of the balancing arms of the bridge and will yield incorrect effective mutual capacitance readings. This means that the meter case must be "floating" above ground. It should be placed on some insulating material. Other wires or objects should not touch the meter case. To obtain very sharp nulls on cable lengths less than one mile, the operators hand may need insulation as the final null is approached (because the body acts as a path from meter case to ground).

3.12 In spite of the precautions stated above, these instruments are widely used and provide good measurement data. For any instrument, read the manual and follow the instructions. If in doubt, it might be better to "float" the bridge. There is a simple test to determine if valid measurements can be made with the instrument grounded. This is shown in Exhibit 2B.

3.13 A review of Appendix 1 might be helpful before preceeding with measurements. Bridges may give results of capacitance (C) and conductance (G) or dissipation (D) in one of three ways.

a. Series mode, Cs and D
b. Parallel mode, Cp and D
c. Parallel mode, Cp and Gp

For cable measurements, the first method is preferred for reasons discussed in earlier paragraphs. This discussion is based on that type of instrument, but the principles apply to the other types as well.

3.14 Connect the capacitance bridge to one end of a cable pair as shown in Exhibit 1. Null the bridge and record the bridge settings. Record both C and D (or G) values even if there are no initial plans to use D values. Record all digits available, even though the last one or possibly two digits may have little meaning. Record all information that could be useful at a later time. This includes cable type, gauge and length, instruments, temperature, etc. Recorded measurement data may mean very little to anyone except the person making the measurements unless the data is organized, labeled, and contains explanatory notes. To aid in organizing your data, a sample data sheet is shown in Exhibit 3.

3.15 If conductance is to be accurately determined, measure the cable pair dc loop resistance also. Measured dc loop resistance can improve the accuracy of capacitance corrections on very long cable sections.

3.2 <u>On the Reel Measurements</u>

3.21 Access the outer end of the reel. Uncap and remove about one foot of sheath material; identify and separate pairs. (Experience will dictate exactly how much sheath must be cut back.) The inner end of the cable must be cleared (separate wires). Remove enough insulation from each conductor to make the measurements; generally one-half inch is sufficient to make individual pair measurements. (More insulation must be removed if the pairs are to be "bunched" and measured. This discussion is limited to individual pair measurements.)

3.22 Note the reel length and cable gauge stated on the reel. Refer to Exhibit 4 for approximate "expected measured values" for that length and gauge. Use short leads with good connections. Connect pair one to the bridge measurement terminals; leave all other pairs "floating." Set the bridge to the "expected measured values". Null the <u>C and D</u> dials for each pair measurement. Record the C and D values for each pair measured. Exhibit 3 shows an example of recorded data. Measure pair 2, 3, etc., in the same manner. The measured values should all be similar and should be near the "expected measured values." If they are not, refer to paragraph 3.3. Cable specifications generally refer to average mutual capacitance of all pairs. This means that all pairs of a cable must be measured if they are to be compared to specification values. (However, conductance is specified on an individual pair basis.)

3.23 When the measurements are complete, cut off the excess conductors and recap the sheath. Replace the reflectorized wrapper to protect cable from potential heat damage.

3.3 Measurement Problems

3.31 If problems are encountered during measurements, the following may aid in locating the cause. (Eliminating the problem may not be possible.) Measurement problems might be caused by wires shorted together or to the shield at the inner end of the reel. Other possible causes are open, shorted or grounded pairs; moisture in the cable core; or other problems.

3.32 If all readings are questionable, use a known capacitor and check out the bridge.

3.33 If all of the pairs measure high C and D, there may be moisture in the cable core. Another indication of moisture in cable has been for the inner pairs to measure only slightly high and the outer pairs to measure much higher C and D than normal. A resistor-capacitor network such as shown in Exhibit 2C can be used to check out both C and D settings of the bridge.

3.34 If only a few pairs of cable are questionable, it might contain opens, shorts or ground. Start by removing the end cap at the inner end of the cable. Try to assure that all bare wire ends are not touching other wires or the shield. This may be difficult with large cables.

3.341 A shorted pair may measure (a) series inductance and resistance, or (b) series capacitance (large values) and resistance. It might be difficult or impossible to obtain a null on most capacitance bridges.

3.342 One wire shorted to ground or another non-mate wire should cause the capacitance to measure high. A high resistance short or ground may have similar effects or may only show an increase in the D value.

3.343 A split pair or an open conductor would cause the pair to measure low capacitance.

3.4 Measuring Long Reel Lengths

3.41 Small size cables such as one through six pairs are sometimes shipped in very long reel lengths. If the reels are longer than 0.1 wavelength (21.4 kF of 19 gauge, 15.4 kF of 22 gauge, 12.3 kF of 24 gauge or 9.8 kF of 26 gauge), another method can be used to more accurately measure capacitance. This consists of accessing both the outer and inner ends of the cable. As shown in Exhibit 2A, connect both tip conductors to one bridge terminal and both ring conductors to the other terminal. This has the effect of measuring two pairs (in parallel) of one-half the length. This would allow measurements on cables up to 0.2 wavelength with the accuracy of 0.1 wavelength. This technique is called "head-to-tail" measurements.

3.42 This procedure is only possible on the reel where both cable ends are accessible at the same location. It is generally not practical to access the inner end of large cables; but large cables are necessarily limited to shorter reel lengths.

3.43 Head-to-tail measurements may be done on a few pairs to establish that correction factors are valid. However, since long cables are generally limited to very few pairs, measurement of all pairs of the cable in this manner is recommended to reduce correction factors and improve accuracy.

3.44 Head-to-tail measurements are especially useful to improve the accuracy of mutual conductance. By measuring at one-half the reel length, conductance accuracy can be improved as much as 4 to 1. The dc loop resistance should always be measured to accurately determine mutual conductance.

3.5 Measurements on Installed Cable

3.51 If mutual capacitance measurements are made on installed cable to verify that cable specifications are met, remember that all pairs of a section must be measured. If it is a check on the condition of older cables, it is generally sufficient to measure only one to three pairs of a section. Select the pairs so that at least one is near the outside of the core (near the shield). If several pairs are measured, include an inner pair also (near the center of the core). The reason for selecting an outer pair is that moisture is likely to affect outer pairs sooner and more severely than inner pairs.

3.52 Assure that the measured cable pair is cut dead and "floating" at the intended distant end. Limit measurement lengths to about one loading section (4500 or 6000 feet). Assure that there are no loading coils or bridge taps in the measurement length. Remove about one-half inch of insulation and connect the cable pair to the bridge terminals. Determine the "expected measured values" from Exhibit 4 knowing the cable length and gauge. Set the bridge at the expected values; null the C and D and record both C and D values.

3.53 The measured values of C and D should be near the expected values. Refer to Paragraph 3.3 if problems is encountered. To the items discussed in Paragraph 3.3, add the effects of loading coils, build out capacitors, and bridge taps. A loading coil near the capacitance bridge will generally result in higher than expected values of capacitance. A loading coil (open circuit) at distant end will have little or no effect on capacitance readings. Build out capacitors and bridge taps will result in higher than expected capacitance values.

3.54 Normal troubleshooting procedures using megger, wheatstone bridge, ohmmeter, wire chief's test set or other test equipment should be used to find faulted pairs. There are some new, more precise methods of

fault location available such as radar or time domain reflectometry (TDR) techinques.

3.55 It is good practice to select an outer pair of each cable installed for test purposes (where the cable is large enough to have spare pairs available). Measure and record C and D initially and at periodic intervals to monitor the condition of each section. In particular, note changes in the D reading, since this will be the first indication of moisture ingress into air core cables.

3.551 To speed up the periodic checking, measure both directions from a common point--such as loading points. The pairs must be cut dead at the distant end. Make sure that there are no loading coils, build out capacitors, or bridge taps on the measured pair. There should be no gauge changes in the measured section if exact values of C and D (or G) are to be used. For example, measure east and west from load points, 1, 3, 5, 7 and 9. Put an insulated sleeve over the pairs at the measurement points for easy access next time. Cut the pairs dead at load point 2, 4, 6, 8 and at the end of the line.

3.6 Miscellaneous: Making accurate mutual capacitance measurements of cable pairs is not difficult. Practice improves this skill--both in measurement and analysis of measurements. These measurements can be very useful in determining the cable condition. But mutual capacitance is only one measure of cable condition. It is most useful in pinpointing the section in trouble. Other tests such as voice and carrier frequency loss, response, crosstalk and noise may be more useful on completed cable circuits.

4. CORRECTION OF MEASUREMENT DATA

4.1 Series Capacitance and D

4.11 Using the series measu are usually accurate (most measurement lengths. Muc mutual conductance on all leng increases because of the large effects).

4.12 Capacitance Correctior capacitance correctior Multiply the measured capacit true mutual capacitance. Exh as a function of the measured most capacitance bridges is o use of dissipation correction the length corrections are ac the resistance, capacitance a dissipation correction factor factors.

4.13 Conductance Correction (Cs & D): True conductance can be determined from measured values by using the following correction:

$$Gt = \left[\frac{D}{\omega Cs} - \frac{Rdc}{3}\right] \omega^2 Ct^2$$

where: Gt = true conductance in mhos

D = measured dissipation factor

ω = 6283

Cs = measured capacitance in farads (series mode)

Rdc = measured dc loop resistance in ohms

Ct = true capacitance in farads (or corrected capacitance)

If the dc loop resistance is not measured, it must be accurately estimated or large errors can result.

4.131 Quick reference charts for converting measured dissipation into true conductance are impractical. Such charts based on nominal resistance and capacitance are much in error for small variations from nominal values. True conductance must be calculated.

4.14 Head-to-Tail Correction (Cs & D): To correct measured capacitance using length corrections (Exhibit 7), enter the graph at one-half the reel length. Capacitance correction factors as a function of dissipation can also be applied to head-to-tail measured capacitance. Exhibit 8 is used for correcting capacitance from either normal or head-to-tail measurements. For conductance corrections from head-to-tail measurements, use the following formula:

$$Gt = \left[\frac{D}{\omega Cs} - \frac{Rdc}{12}\right] \omega^2 Ct^2$$

Head-to-tail measurements allow for much greater accuracy in determining conductance than the normal measurements and formula in paragraph 4.13.

4.2 Parallel Capacitance and Dissipation (Cp & D)

4.21 Corrections to measured capacitance are required on shorter measurement lengths using the parallel measurement bridge than using the series measurement bridge. At 0.1 wavelength, a correction of 6 to 8 percent is required for parallel measurements; but only a one percent or less correction is required for series measurements. Larger corrections require more care in both measurements and corrections of measured data.

4.22 Capacitance Correction (Cp & D): From Exhibit 9, determine the capacitance correction factor for the cable length measured. Multiply the measured capacitance by the correction factor to determine the true mutual capacitance. Exhibit 10 provides correction factors as a function of the measured dissipation factor. As with the series bridge, the dissipation corrections should primarily be used for verifying that the length corrections are accurate.

4.23 Conductance Correction (Cp & D): True conductance can be determined from the measured values by using the following correction:

$$Gt = \omega CpD - \frac{Rdc}{3}\omega^2 Ct^2$$

where Gt = true conductance in ohms

ω = 6283

Cp = measured capacitance in farads (parallel mode)

D = measured dissipation factor

Rdc = measured dc loop resistance in ohms

Ct = true capacitance in farads (or corrected capacitance)

This formula provides a reasonable correction for conductance for lengths not exceeding 0.06 wavelength. At 0.06 wavelength, the measured capacitance Cp is in error about one percent. If the dc loop resistance is not measured, it must be accurately estimated or large errors can result.

4.24 Head-to-Tail Correction (
using length corrections
the reel length. Capacitance cor
the same for normal or head-to-ta
corrections. For conductance cor
the following formula:

$$Gt = CpD$$

This formula provides a reasonabl
not exceeding 0.12 wavelengths (

4.3 Parallel Capacitance and

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4.24 Head-to-Tail Correction (Cp & D): To correct measured capacitance using length corrections (Exhibit 9), enter the graph at one-half the reel length. Capacitance corrections as a function of dissipation are the same for normal or head-to-tail measurements. Use Exhibit 10 for these corrections. For conductance corrections from head-to-tail measurements use the following formula:

$$Gt = CpD - \frac{Rdc}{12}\omega^2 Ct^2$$

This formula provides a reasonable correction for conductance for lengths not exceeding 0.12 wavelengths (Cp is in error by about one percent).

4.3 Parallel Capacitance and Conductance (Cp & Gp)

4.31 The same corrections apply to parallel measured capacitance and conductance as to parallel capacitance and dissipation. Thus, length corrections are the same. To use the dissipation correction factors for measured capacitance, the measured conductance must first be converted to dissipation:

$$D = \frac{Gp}{\omega Cp}$$

The calculated dissipation can be used as if it were measured.

4.32 Conductance Correction (Cp & Gp): True conductance can be determined from the measured values by using the following correction:

$$Gt = Gp - \frac{Rdc}{3} \omega^2 Ct^2$$

where: Gt = true conductance in mhos

Rdc = measured conductance in mhos

Ct = true capacitance in farads (or corrected capacitance)

If the dc loop resistance is not measured, it must be accurately estimated or large errors can result. As discussed in paragraph 4.23, errors in conductance can result at lengths over 0.06 wavelengths.

4.33 Head-to-Tail Correction (Cp & Gp): To correct measured capacitance using length corrections (Exhibit 9), enter the graph at one-half the reel length. There is no change in dissipation corrections to measured capacitance. For conductance corrections from head-to-tail measurements, use the following formula:

$$Gt = Gp - \frac{Rdc}{12} \omega^2 Ct^2$$

As discussed in paragraph 4.24, errors can result at lengths over 0.12 wavelengths. Also, dc loop resistance must be measured or accurately estimated.

5. MEASUREMENT ERROR AND LIMITATIONS

5.1 There are certain errors and limitations associated with all measurements. This will briefly discuss the practical errors and limitations associated with capacitance measurements. First, several sources of measurement error will be outlined. Then, some practical limitation and error margins will be suggested for series and parallel mode capacitance measurements.

5.11 The errors in capacitance measuremen

a. Human Error

b. Instrument Error

c. Propagation Effects

These error sources will be discussed sepa[illegible] interrelate to some degree, and the net er[illegible] bination of factors.

5.12 Human error can be decreased by training--and this can be self training through the repeated use of the capacitance bridge. Finding an exact null on the bridge can be awkward at times. Repeated use improves the ability to be more precise in finding nulls and reading values. Repeated use builds confidence in the measurement results.

5.13 Instrument error can be separated into several parts. Become familiar with the stated accuracy of the capacitance bridge. Accuracy is often expressed in percent of full scale plus dial increments. Some bridges state a very high accuracy for capacitance (0.1 percent error); but most field instruments state a 1.0 percent maximum error. Conductance and dissipation factor are less precise. These are often stated to be about 5 percent maximum error, and possibly more. Capacitance bridges with built in 1000 hertz oscillators generally have a frequency accuracy of about 2 percent error. Frequency error has little effect on capacitance, but can have a major effect on dissipation and conductance accuracy.

5.14 Because of propagation effects, the capacitance bridge measures the "apparent" capacitance and dissipation factor or conductance of cable pairs. Through the use of correction factors, "true" or corrected values of capacitance and conductance can be obtained. These corrections are based on transmission line concepts established more than 50 years ago. Correction factors based on nominal values of cable parameters can be used to a high degree of accuracy provided (a) the measurement length is limited; and (b) the departure from nominal values is limited. Thus, it is not only possible, it is practical to measure cable mutual capacitance and determine compliance within specifications. This is because the cable mutual capacitance must be near the specified value for compliance. and the corrections are more accurate near these values. When the capacitance departs fro corrections can occur. But exact val there is a large departure from cab

5.141 The determination of mutua measurement is difficult f masking of the leakage conductance tremely difficult to obtain accura conductance is very low. Accurate a percentage basis are not general very low (less than 0.1 micromhos

5.2 Series Capacitance and Dis

5.21 For field measurements on measurement mode is prefer 0.1 wavelength, less than one perc is required. That is 21.4, 15.4, and 26 gauge cable. By allowing accurate capacitance measurements

That is 32.2, 23.1, 18.4 and 14.7 kilofoot for 19, 22, 24, and 26 gauge cable. DC loop resistance must be measured to assure accuracy beyond 0.1 wavelength. It is suggested that about one percent error be allowed for the combined effect of human, instrument and propagation error after capacitance corrections are made.

5.22 To determine cable mutual conductance accurately, dc loop resistance must be measured at the same time capacitance is measured. The conductance correction increases as the square of the length. If the length is doubled, the conductance correction is 4 times as great. Thus, the measurement error can be 4 times as great for twice the measurement length. In general, try to limit the measurement length to 0.05 wavelength for accurate mutual conductance. That is 10.7, 7.7, 6.1 and 4.9 kilofoot of 19, 22, 24 and 26 gauge cable. Refer to the test instrument manual for accuracy specifications.

5.23 Head-to-tail measurements greatly improve the accuracy of conductance measurements because of the smaller corrections required. The measurement length should be limited to 0.1 wavelength.

REFERENCES

1. J. V. Buscemi and A. E. Widmer, "Apparent Errors in the Measurement of Mutual Capacitance on Longer Lengths of Cable Pair at 1000 CPS." Presented at the Thirteenth Annual Wire and Cable Symposium, December 2, 1964.

2. R. A. Frisch, I. Kolodny and J. A. Olszewski, "Simplified Determination of Low Frequency Mutual Capacitance of Long Lengths of Telephone Cables." Presented at the Sixteenth International Wire and Cable Symposium, November 29, 30 and December 1, 1967.

3. T. Lamar Moore and Kenneth W. Brownell, Jr., "Mutual Capacitance Correction Factors for Series Mode Bridges." Presented at the 23rd International Wire and Cable Symposium, December 3-5, 1974.

4. T. Lamar Moore, "Cable Capacitance Measurements." Presented at the 1974 REA Telephone Engineering Symposium, February and March 1974.

APPENDIX I

Layman's Guide to Capacitance Measurements

1. INTRODUCTION

1.1 This appendix will briefly explore propagation effects and the related apparent measurement errors. All discussion will refer to the propagation effects of 1000 hertz signals.

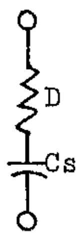
1.2 A cable pair effectively consists of series resistance and inductance (R and L) and parallel (or shunt) conductance and capacitance (G and C). As the 1000 hertz signal travels down the wire pair, it is altered by this R, L, G and C. The signal arriving at the distant end has been affected by loss and by phase change.

1.3 When the mutual capacitance of a cable pair is measured, the cable R, L, G and C cause small errors in this measurement. An "apparent" capacitance and conductance (or dissipation) is measured. The propagation effects of transmission lines are well established, and these apparent values can be converted into true values by applying "corrections". Each minute change along the cable pair affects the accuracy of determining "true" values from measured values. Also, the accuracy of the test equipment affects the accuracy in converting measured values into true values. A small percentage error in a measured value can sometimes result in a much larger percentage error in the corrected "true" value. These effects must be dealt with in a practical basis.

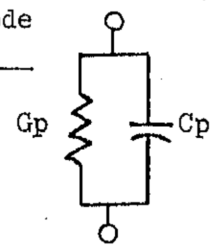
2. BRIDGE MEASUREMENT METHODS

2.1 Impedance bridges and capacitance bridges measure capacitance in a series mode or a parallel mode. The Electro Scientific Industries 250 DE is representative of bridges measuring in the series mode and the Siemens 3R 217p is representative of bridges measuring in the parallel mode.

Series Mode (ESI)



Parallel Mode (Siemens)



2.2 Series Measurement Mode: There is a variety of low cost bridges that measure Rs and Cs in a series mode. Most of these bridges express the resistance added to the balancing arm of the bridge in terms of D factor or dissipation.

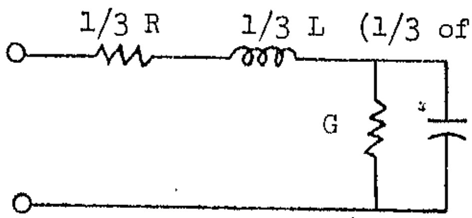
2.3 Parallel Measurement Mode: The parallel mode of measurement is usually expressed in Gp and Cp as shown. Some parallel mode bridges also express measurements in D and Cp, where D is a measure of the conductance (Gp) added to the balancing arm of the bridge required to obtain a null.

2.4 Exhibit 12 shows how the "apparent" or measured capacitance (26 gauge cable, 0.083 microfarads per mile) departs from the true value at longer measurement lengths. Notice that the series measurement values of capacitance are less affected by length than are parallel values. Thus, smaller corrections are required for Cs than for Cp for longer measurement lengths.

3. SIMPLIFIED DESCRIPTION

3.1 The reason that the Cs requires less correction is that it better represents the "apparent" transmission line as viewed from one end with an open circuit at the distant end. Except for short lengths of cable, the conductance or dissipation arm of the bridge is primarily balancing out the effects the series resistance, rather than the shunt conductance.

3.2 For cable lengths up to one-tenth wavelength, the open circuit cable parameters might be approximated with the following network:

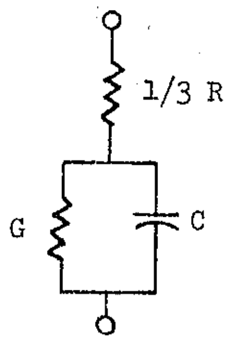


(1/3 of the loop resistance and inductance)

(approximate true values)

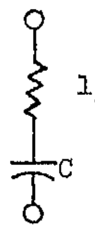
In other words, the cable capacitance and conductance might appear to be "lumped" at one-third the distance from the measuring end.

3.3 The series inductance plays a minor role in the propagation effects at 1000 hertz. If the L were omitted, the network would appear as:



3.31 More than a decade ago, it was proposed that a capacitance bridge be developed with balancing arms as shown above. One third of the loop resistance could be set on the series balancing arm and then the G and C could be balanced and read directly, without large corrections.

3.4 For relatively dry cable, G also plays a minor role in the propagation effects. If the L and G are omitted, the network would appear as:



3.41 Many small portable capacitance bridges measure D and C, where D is primarily balancing out the effects of one third of the loop resistance and the actual capacitance with a reasonable accuracy.

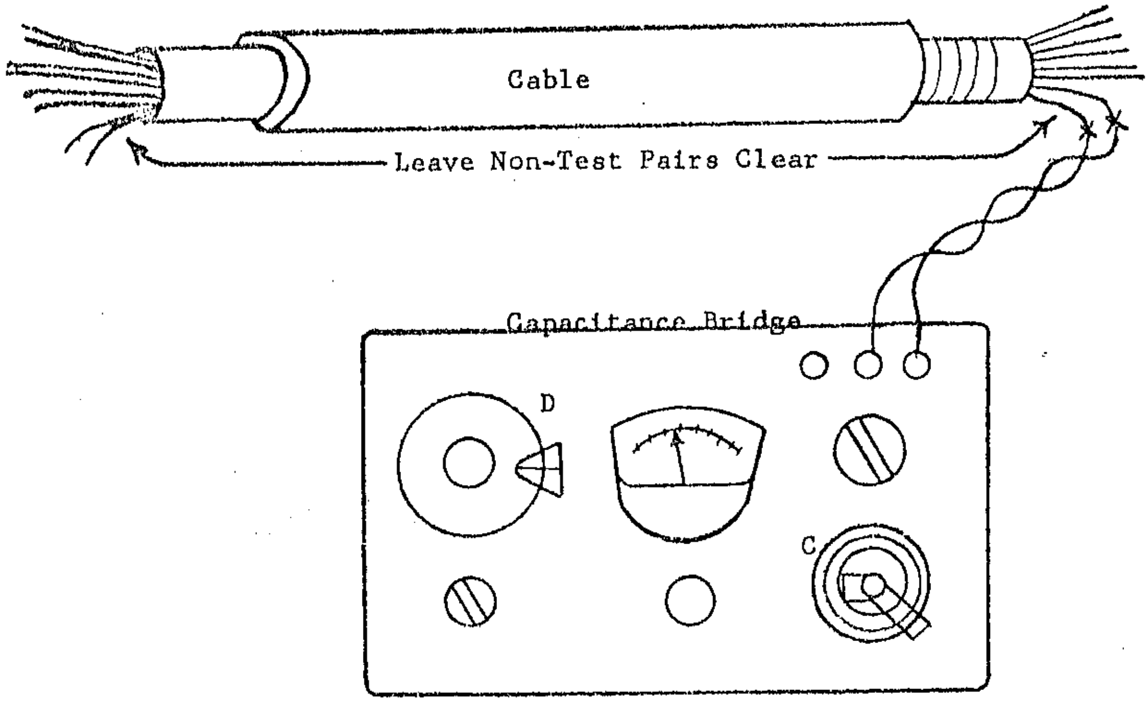
3.5 The preceeding discussion is an oversimplification of the propagation effects and 1000 hertz capacitance measurements. But it does serve as an explanation to show why capacitance measured in the series mode requires less correction than the parallel measured capacitance at longer measurement lengths. If the measured D is less than 0.1, the Cp, Cs and true C are all within one percent.

4. MUTUAL CONDUCTANCE

4.1 The determination of cable conductance from an open circuit measurement is difficult for long lengths of cable due to the masking of the shunt conductance by the series resistance. It is extremely difficult to obtain accurate conductance readings when true conductance is very low; but, at the same time, accurate field results are not generally required when the conductance is low. However, conductance in the 3.3 micromho per mile range and larger is of practical field interest. Within certain accuracy limitations, it is possible to measure conductance on moderate cable lengths.

EXHIBIT 1

CABLE CAPACITANCE MEASUREMENTS

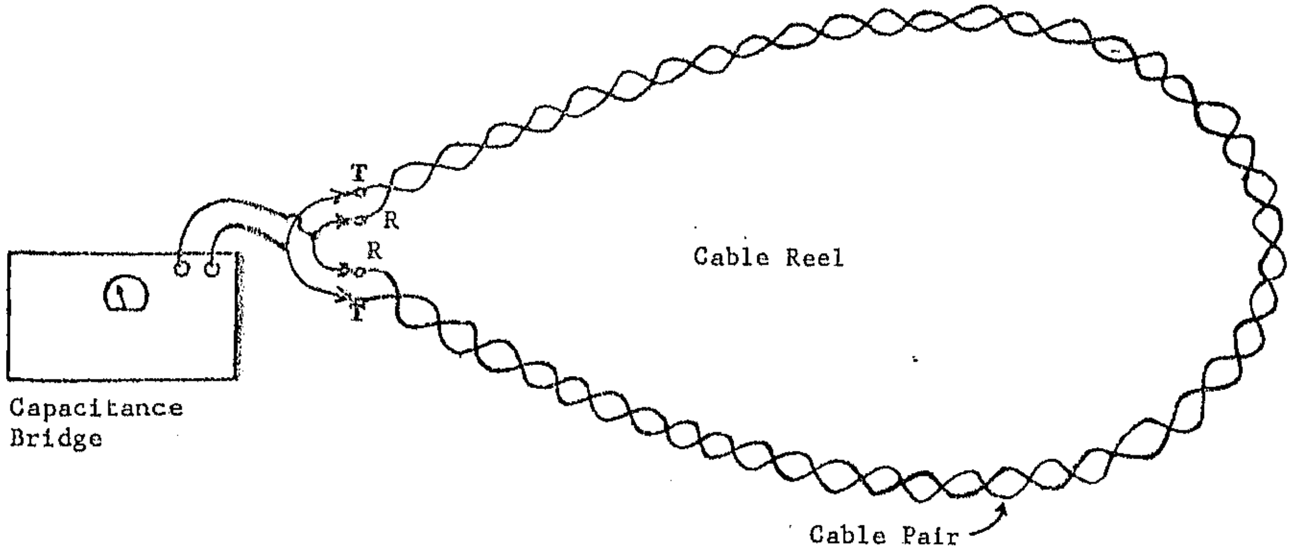


Notes:
1. Refer to the capacitor bridge instruction manual for specific instructions.
2. Unless you know that the bridge should be grounded, set the bridge on insulation material and do not let non-test pairs or cable shield contact the bridge case.
3. Connect the test pair to bridge terminals; all other pairs should be left clear.
4. Measure at 1 kHz; set bridge dials near the C and D values expected. Continue adjust of C and D dials (alternately) until the lowest meter reading is obtained (null).
5. Record C and D values (all available digits).

EXHIBIT 2

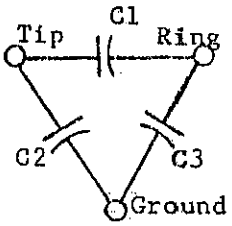
MISCELLANEOUS CAPACITANCE MEASUREMENTS

A. Head-to-Tail Measurements



Head-to-tail measurements can be made when cable is on the reel to effectively divide the length by two. The effect is the same as measuring two pairs in parallel of one-half the length.

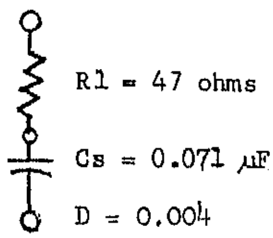
B. Bridge Ground Test



C1, C2 and C3 approx. 0.03 µF

1. Select 3 capacitors of equal value.
2. Measure each value and record.
3. Construct network as shown.
4. Measure tip to ring with
   (a) ground to meter case
   (b) no ground
5. Compare measurements
6. $C\ meas = C1 + \frac{C2 \times C3}{C2 + C3} = 0.045\ \mu F$ (approx)

C. Sample R-C Network



Capacitor Measures:

Cs = 0.071 µF
D = 0.004 (Rs = 8.5 ohms)

With 47 ohms in series (R1) bridge should measure:

Cs = 0.071 µF
D = 0.025

NOTE: Exact value of D will depend on capacitor D value and added resistor value.

IBIT 3
LE DATA AND CALCULATIONS (Cs & D)

546 Feet 12 Pairs 22 Gauge Date 8-7-77

R	Cs(μF)	D	Ct(μF)	Gt(μυ)
	0.1728	0.135	SAME	10.3
	0.1705	0.138	As Cs	15.1
	0.1668	0.135		
	0.1663	0.132		
	0.1680	0.135		
	0.1722	0.135		
	0.1677	0.130		
	0.1708	0.130		
	0.1692	0.130		
	0.1672	0.130		
	0.1720	0.132		
	0.1696	0.130		
M	2.0331			
G.	0.1694		0.0848/MILE	OK

SAMPLE

Spec. 22 Temp. EST. 75°F Test Set ESI 250 DE
Corr. Fac. 0.998 (DO NOT CORRECT)

RESISTANCE ESTIMATED -- 10% ALLOWANCE FOR G ERROR, APPROXIMATELY 12.5μυ. EXACT G CANNOT BE DETERMINED AT 10.5KF.

EXHIBIT 4

EXPECTED MEASURED VALUES: Cs & D

LENGTH (KF)	TRUE CAP. (µF)	EXPECTED MEASURED VALUES OF Cs AND D								
		19 GA.		22 GA.		24 GA.		26 GA.		
		Cs(µF)	D	Cs(µF)	D	Cs(µF)	D	Cs(µF)	D	
1	0.0157	0.0157	0.001	0.0157	0.001	0.0157	0.002	0.0157	0.003	
2	0.0314	0.0314	0.002	0.0314	0.004	0.0314	0.007	0.0314	0.011	
3	0.0472	0.0472	0.005	0.0472	0.010	0.0472	0.015	0.0472	0.024	
4	0.0629	0.0629	0.008	0.0629	0.017	0.0629	0.027	0.0629	0.043	0.05λ
5	0.0786	0.0787	0.013	0.0787	0.027	0.0787	0.043	0.0786	0.067	
6	0.0943	0.0945	0.019	0.0944	0.038	0.0944	0.062	0.0943	0.097	
7	0.1100	0.1103	0.026	0.1102	0.052	0.1101	0.084	0.1099	0.131	
8	0.1256	0.1261	0.034	0.1260	0.068	0.1258	0.109	0.1254	0.171	
9	0.1415	0.1419	0.043	0.1418	0.087	0.1414	0.138	0.1406	0.216	0.10λ
10	0.1572	0.1578	0.053	0.1575	0.107	0.1570	0.171	0.1556	0.265	
11	0.1729	0.1737	0.065	0.1732	0.129	0.1723	0.206	0.1702	0.319	
12	0.1886	0.1896	0.077	0.1889	0.154	0.1875	0.244	0.1843	0.376	
13	0.2044	0.2055	0.090	0.2045	0.181	0.2025	0.286	0.1977	0.436	
14	0.2201	0.2215	0.105	0.2200	0.209	0.2170	0.329	0.2104	0.497	0.15λ
15	0.2358	0.2374	0.120	0.2353	0.240	0.2312	0.375	0.2221	0.560	
16	0.2515	0.2534	0.137	0.2505	0.272	0.2449	0.423			
17	0.2672	0.2693	0.155	0.2655	0.306	0.2580	0.472			
18	0.2830	0.2852	0.174	0.2801	0.342	0.2704	0.523			
19	0.2987	0.3011	0.194	0.2945	0.379	0.2820	0.573			
20	0.3144	0.3170	0.215	0.3085	0.417					
21	0.3301	0.3327	0.237	0.3220	0.456					
22	0.3458	0.3484	0.260	0.3350	0.497					
23	0.3616	0.3640	0.284	0.3475	0.537					
24	0.3773	0.3795	0.308	0.3594	0.578					
25	0.3930	0.3948	0.334							
26	0.4087	0.4100	0.361							
27	0.4244	0.4249	0.388							
28	0.4402	0.4396	0.416							
29	0.4559	0.4540	0.445							
30	0.4716	0.4681	0.475							

Notes: Frequency=1000 hertz. R=85,171,274 or 431 ohms per mile for 19, 22, 24 or 26 gauge cable. L=1.09 millihenry per mile. G=0.001 micromho per mile. C=0.083 microfarad per mile.

(KF)	(µF)	Cp(µF)	D	Cp(µF)	D	Cp(µF)	D	Cp(µF)	D	
1	0.0157	0.0157	0.001	0.0157	0.001	0.0157	0.002	0.0157	0.003	
2	0.0314	0.0314	0.002	0.0314	0.004	0.0314	0.007	0.0314	0.011	
3	0.0472	0.0472	0.005	0.0472	0.010	0.0472	0.015	0.0471	0.024	
4	0.0627	0.0629	0.008	0.0629	0.017	0.0629	0.027	0.0628	0.043	
5	0.0786	0.0787	0.013	0.0786	0.027	0.0785	0.043	0.0783	0.067	0.05 λ
6	0.0943	0.0944	0.019	0.0943	0.038	0.0940	0.062	0.0934	0.097	
7	0.1100	0.1102	0.026	0.1099	0.052	0.1094	0.084	0.1080	0.131	
8	0.1256	0.1259	0.034	0.1254	0.068	0.1243	0.109	0.1213	0.171	
9	0.1415	0.1417	0.043	0.1407	0.087	0.1388	0.138	0.1344	0.216	
10	0.1572	0.1573	0.053	0.1557	0.107	0.1525	0.171	0.1454	0.265	0.10 λ
11	0.1729	0.1730	0.065	0.1704	0.129	0.1653	0.206	0.1545	0.319	
12	0.1886	0.1885	0.077	0.1845	0.154	0.1770	0.244	0.1615	0.376	
13	0.2044	0.2039	0.090	0.1981	0.181	0.1872	0.286	0.1662	0.436	
14	0.2201	0.2190	0.105	0.2108	0.209	0.1958	0.329	0.1687	0.497	
15	0.2358	0.2340	0.120	0.2226	0.240	0.2027	0.375	0.1691	0.560	0.15 λ
16	0.2515	0.2487	0.137	0.2333	0.272	0.2077	0.423			
17	0.2672	0.2630	0.155	0.2427	0.306	0.2109	0.472			
18	0.2830	0.2769	0.174	0.2509	0.342	0.2124	0.523			
19	0.2987	0.2902	0.194	0.2576	0.379	0.2122	0.573			
20	0.3144	0.3030	0.215	0.2628	0.417					
21	0.3301	0.3151	0.237	0.2665	0.456					
22	0.3458	0.3264	0.260	0.2688	0.497					
23	0.3616	0.3369	0.284	0.2697	0.537					
24	0.3773	0.3465	0.308	0.2693	0.578					
25	0.3930	0.3551	0.334							
26	0.4087	0.3627	0.361							
27	0.4244	0.3692	0.388							
28	0.4402	0.3746	0.416							
29	0.4559	0.3789	0.445							
30	0.4716	0.3821	0.475							

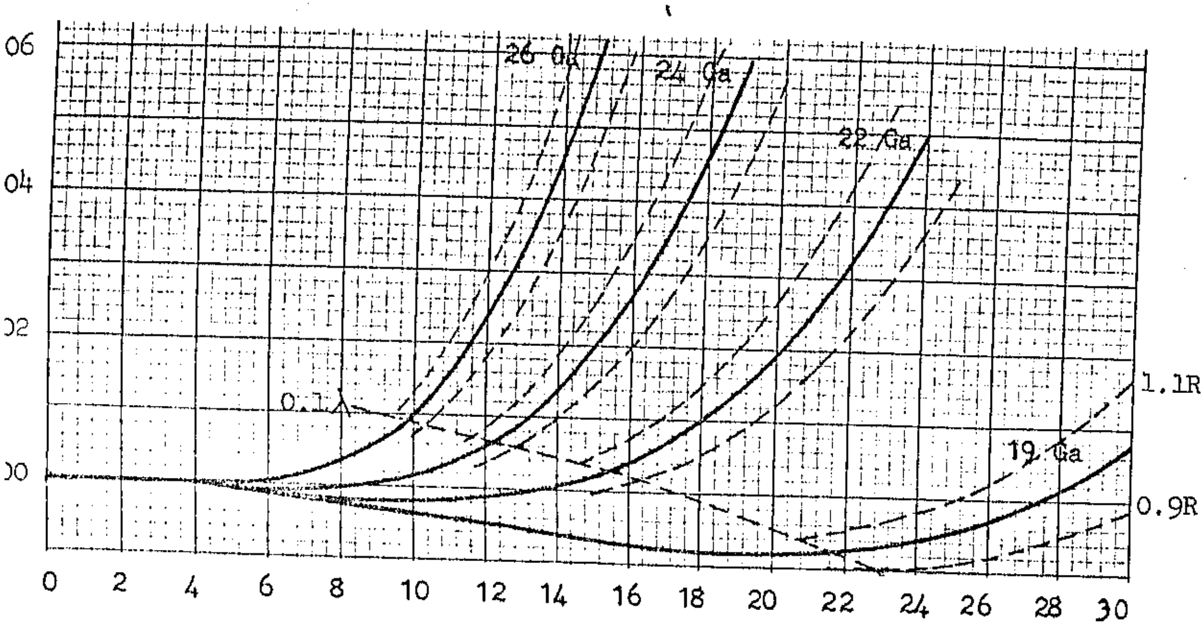
Notes: Frequency=1000 hertz. R=85,171,274 or 431 ohms per mile for 19, 22, 24 or 26 gauge cable. L=1.09 millihenry per mile. G=0.001 micromho per mile. C=0.083 microfarad per mile.

LENGTH (KF)	TRUE CAP. (µF)	EXPECTED MEASURED VALUES OF Cp AND Gp								
		19 GA.		22 GA.		24 GA.		26 GA.		
		Cp(µF)	Gp(µ℧)	Cp(µF)	Gp(µ℧)	Cp(µF)	Gp(µ℧)	Cp(µF)	Gp(µ℧)	
1	0.0157	0.0157	0.05	0.0157	0.11	0.0157	0.17	0.0157	0.26	
2	0.0314	0.0314	0.42	0.0314	0.84	0.0314	1.35	0.0314	2.12	
3	0.0472	0.0472	1.42	0.0472	2.85	0.0472	4.56	0.0471	7.17	
4	0.0629	0.0629	3.36	0.0629	6.75	0.0629	10.81	0.0628	16.97	
5	0.0786	0.0787	6.56	0.0786	13.19	0.0785	21.09	0.0783	33.05	0.05λ
6	0.0943	0.0944	11.34	0.0943	22.78	0.0940	36.38	0.0934	56.77	
7	0.1100	0.1102	18.03	0.1099	36.16	0.1094	57.58	0.1080	89.24	
8	0.1256	0.1259	26.93	0.1254	53.91	0.1243	85.47	0.1218	131.12	
9	0.1415	0.1417	38.38	0.1407	76.58	0.1388	120.65	0.1344	182.43	
10	0.1572	0.1573	52.67	0.1557	104.65	0.1525	163.47	0.1454	242.44	0.10λ
11	0.1729	0.1730	70.12	0.1704	138.53	0.1653	213.94	0.1545	309.53	
12	0.1886	0.1885	91.03	0.1845	178.48	0.1770	271.66	0.1615	381.31	
13	0.2044	0.2039	115.65	0.1981	224.63	0.1872	335.80	0.1662	454.83	
14	0.2201	0.2190	144.26	0.2108	276.90	0.1958	405.08	0.1687	526.97	
15	0.2358	0.2340	177.07	0.2226	335.04	0.2027	477.85	0.1691	594.81	0.15λ
16	0.2515	0.2487	214.26	0.2333	398.53	0.2077	552.18			
17	0.2672	0.2630	255.97	0.2427	466.65	0.2109	626.04			
18	0.2830	0.2769	302.27	0.2509	538.45	0.2124	697.43			
19	0.2987	0.2902	353.17	0.2576	612.81	0.2122	764.60			
20	0.3144	0.3030	408.62	0.2628	688.47					
21	0.3301	0.3151	468.46	0.2665	764.14					
22	0.3458	0.3264	532.46	0.2688	838.48					
23	0.3616	0.3369	600.31	0.2697	910.28					
24	0.3773	0.3465	671.59	0.2693	978.43					
25	0.3930	0.3551	745.82							
26	0.4087	0.3627	822.42							
27	0.4244	0.3692	900.77							
28	0.4402	0.3746	980.18							
29	0.4559	0.3789	1059.94							
30	0.4716	0.3821	1139.34							

Notes: Frequency=1000 hertz. R=85,171,274 or 431 ohms per mile for 19, 22, 24 or 26 gauge cable. L=1.09 millihenry per mile. G=0.001 micromho per mile. C=0.083 microfarad per mile.

EXHIBIT 7

Series Capacitance Correction Factors as a Function of Length (Cs & D)



Note: R = 85,171,274 or 431 ohms per mile for 19, 22, 24 or 26 gauge cable.

EXHIBIT 8

Series Capacitance Correction Factors as a Function of Dissipation (Cs & D)

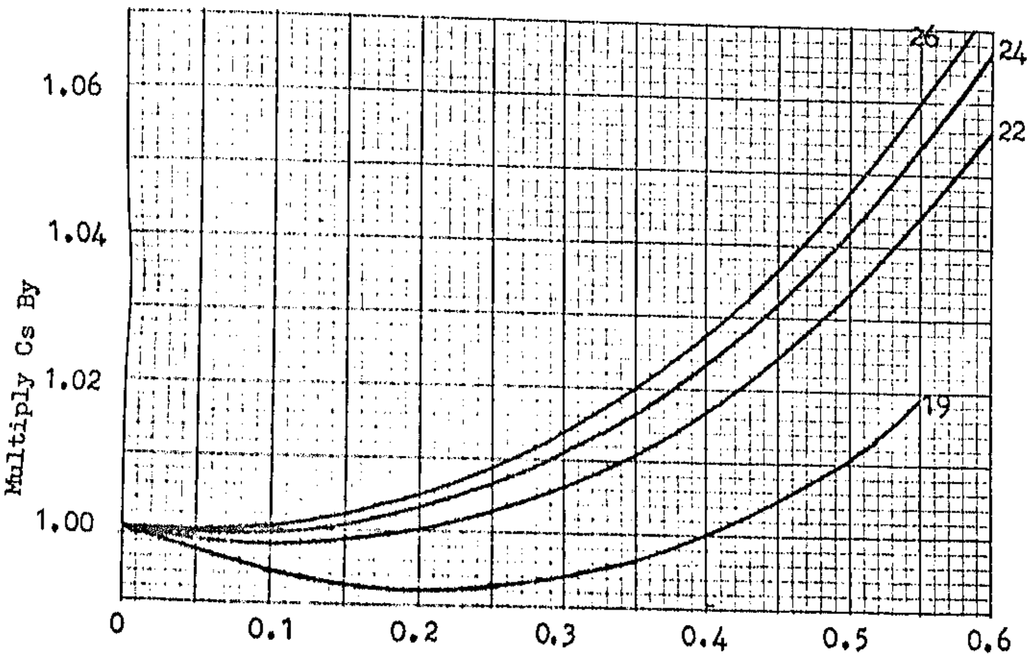


EXHIBIT 9

Parallel Capacitance Correction Factors as a Function of Length
(Cp & D or Cp & Gp)

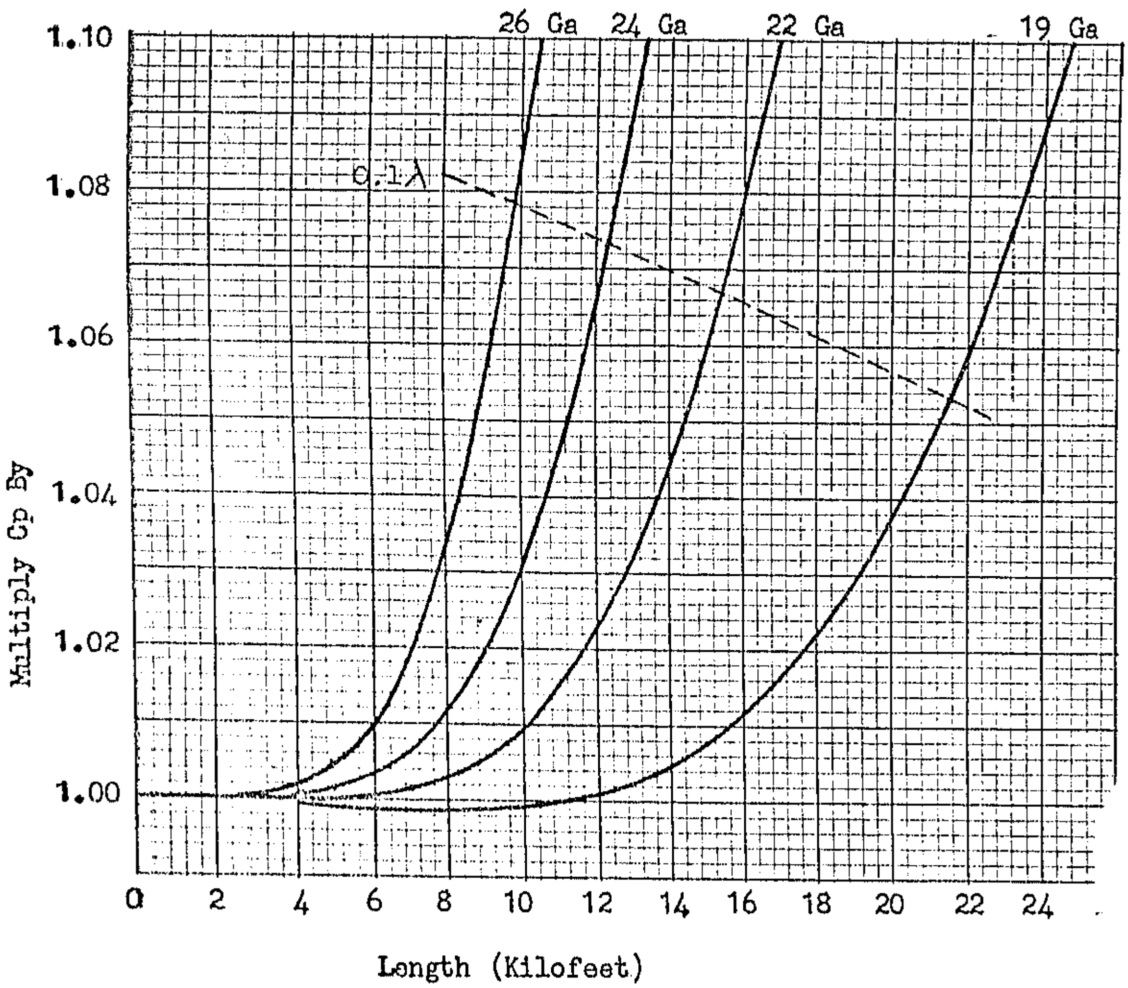


EXHIBIT 10

Parallel Capacitance Correction Factors as a Function of Dissipation
(Cp & D)

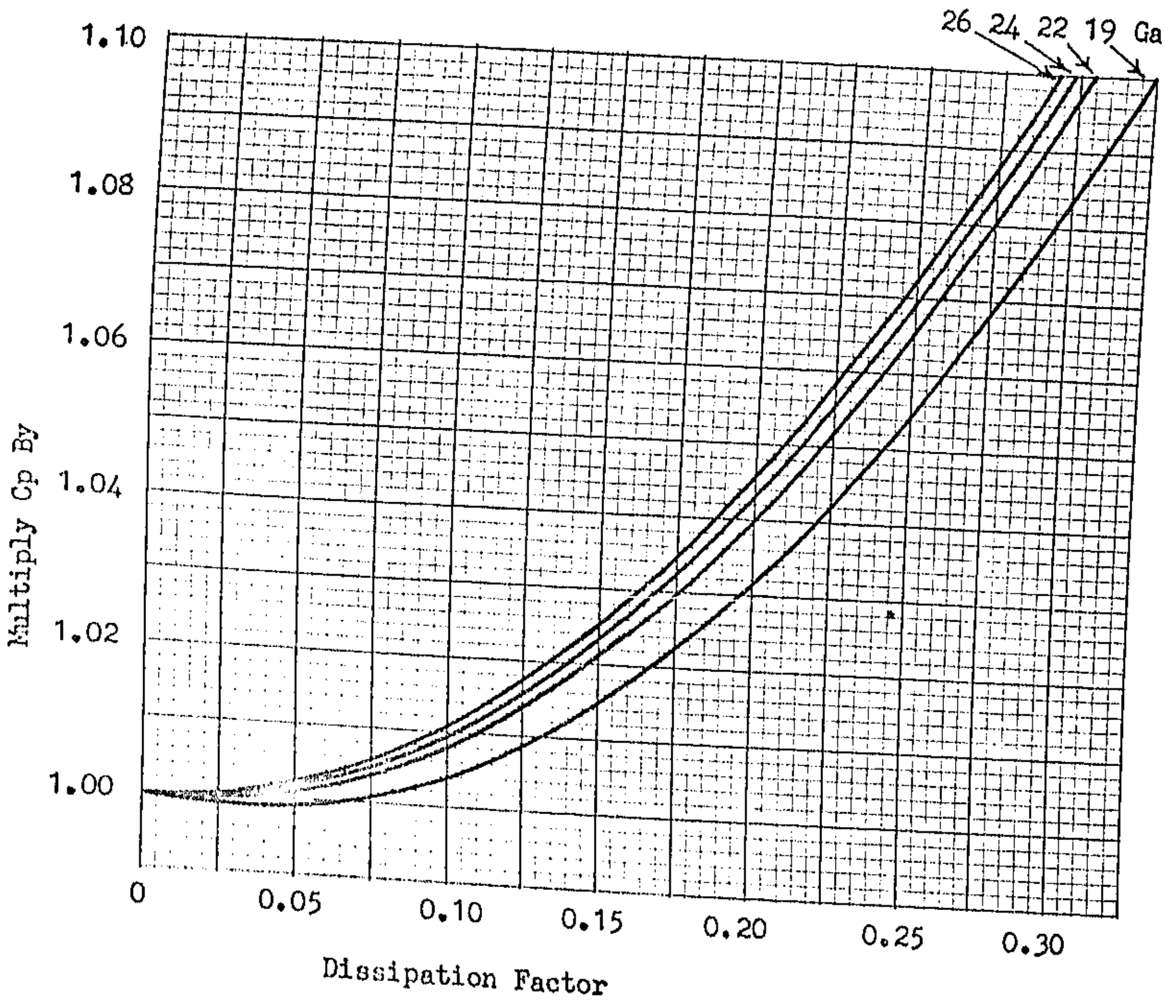


EXHIBIT 11

MISCELLANEOUS DATA

A. Primary Parameters

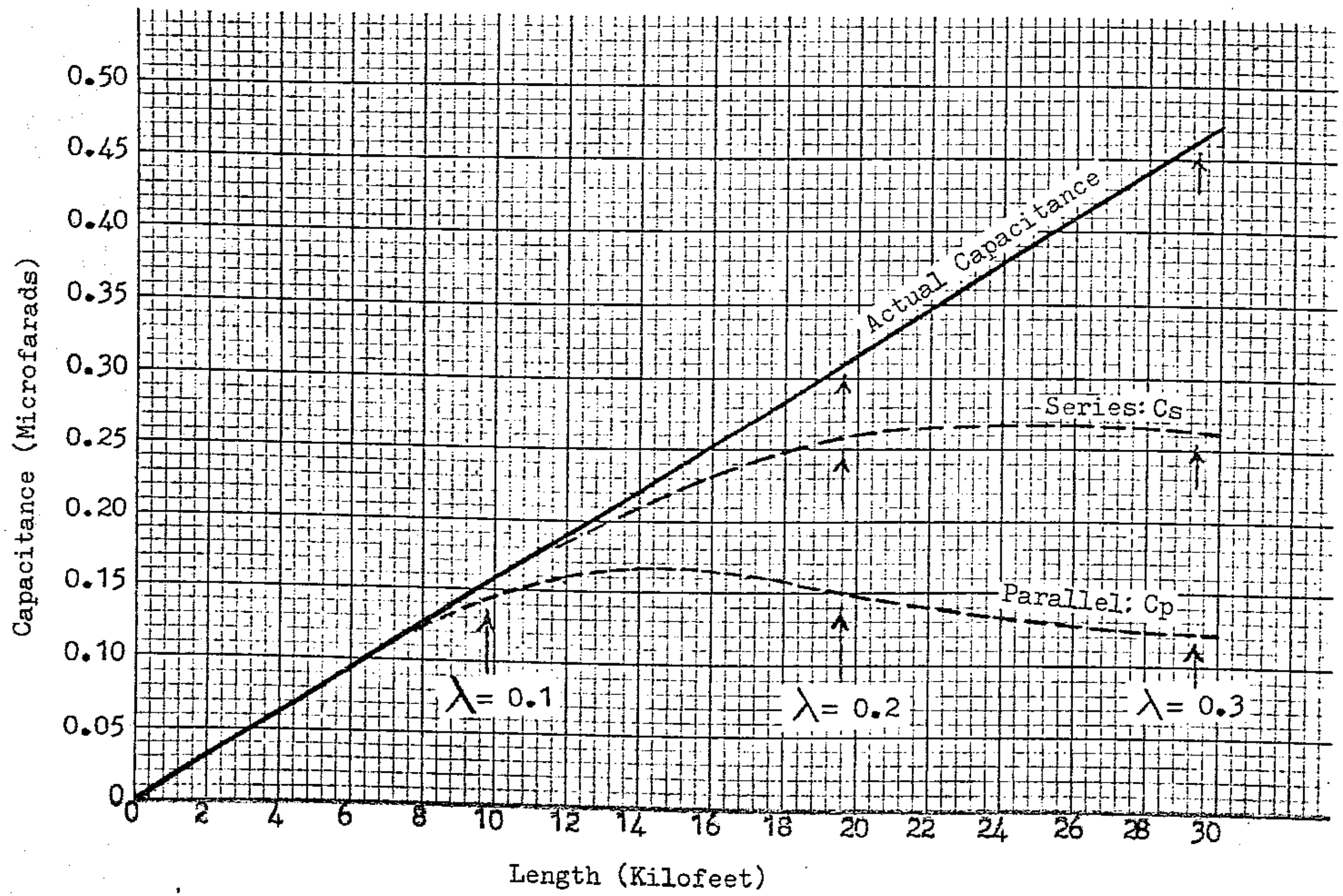
The following nominal 1000 hertz primary cable parameters were used in developing the charts shown in this section. Variation from these values were also used to determine their effects

Parameter	19 Ga.	22 Ga.	24 Ga.	26 Ga.
Resistance (ohms/mile)	85	171	274	431
Inductance (Millihenries/mile	1.09	1.09	1.09	1.09
Conductance (micromhos/mile	0.0001	0.0001	0.0001	0.0001
Capacitance (microfarads/mile	0.083	0.083	0.083	0.083

B. Wavelength in Kilofeet at 1000 Hertz

Cable	0.05 λ	0.10 λ	0.15 λ	0.20 λ	λ
19 Ga.	10.7	21.4	32.2	42.8	214
22 Ga.	7.7	15.4	23.1	30.8	154
24 Ga.	6.2	12.3	18.5	24.6	123
26 Ga.	4.9	9.8	14.7	19.6	98

ACTUAL AND MEASURED CAPACITANCE AS FUNCTION OF LENGTH



NOTE: Capacitance of 26 gauge cable at 0.083 μF per mile.

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